Dynamical instabilities in systems of multiple short-period planets are likely driven by secular chaos: a case study of Kepler-102

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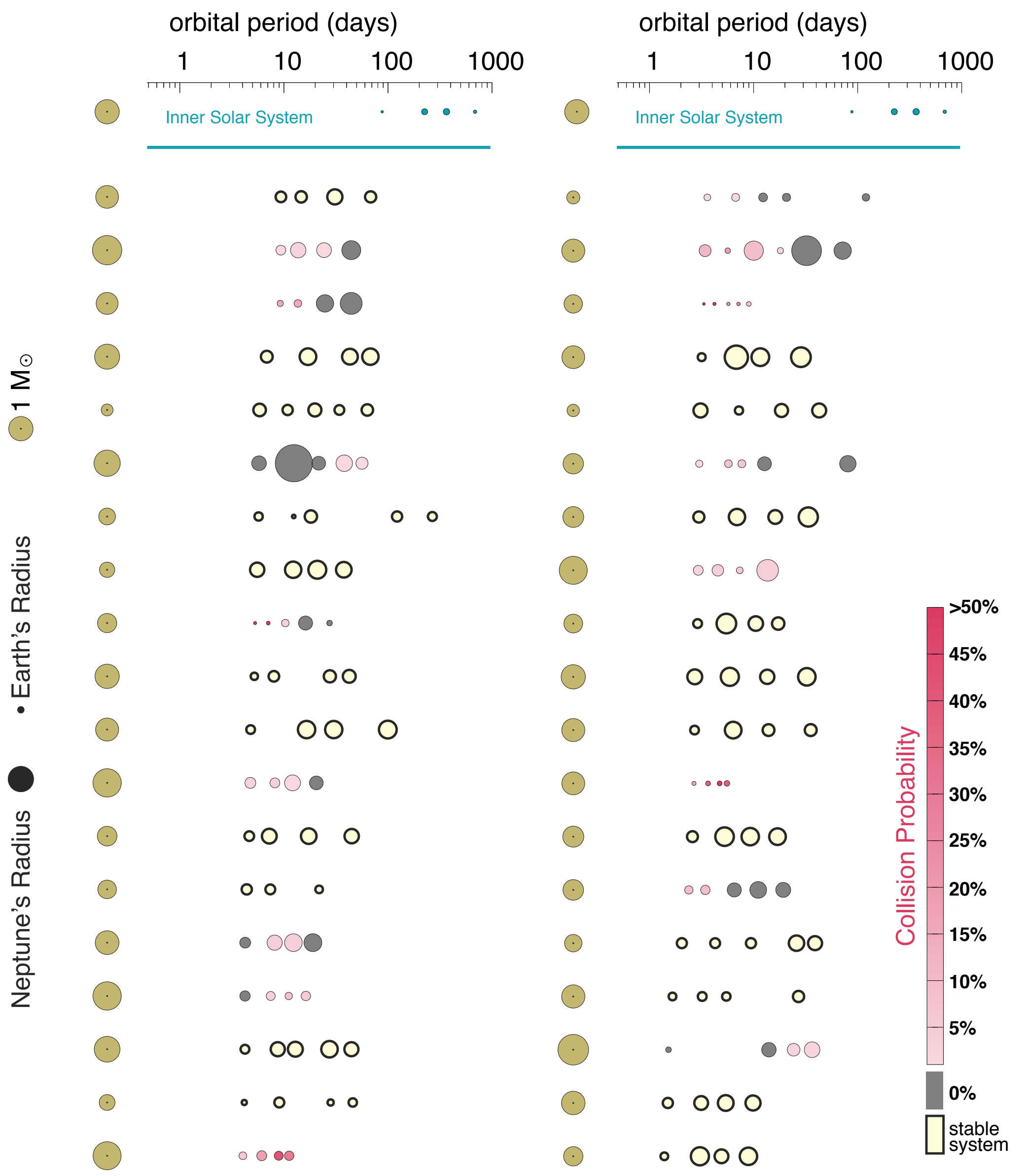
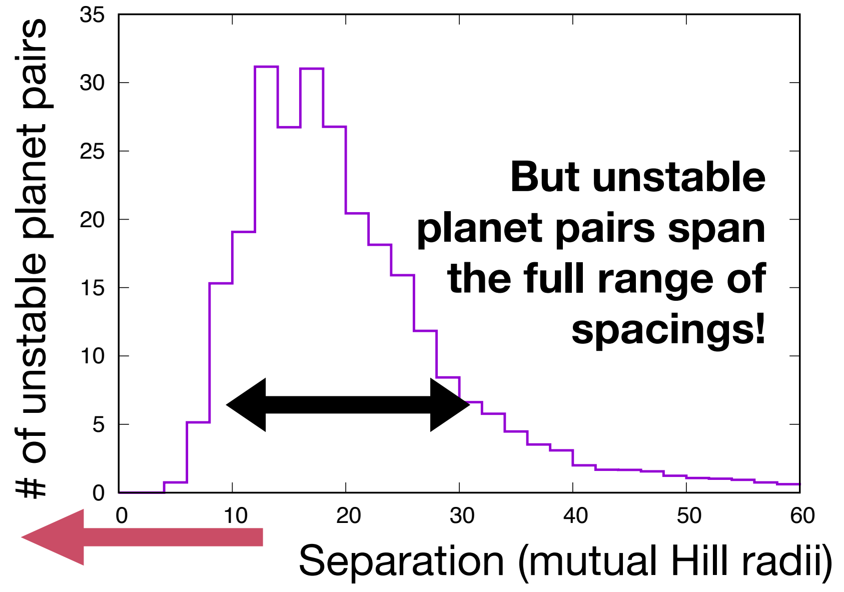
Background: Simulated planetary systems based on the architecture of observed Kepler multis frequently show dynamical instabilities. (We assign masses based on a mass-radius relationship, assign low eccentricities and inclinations, randomize orbital angles, and simulate for 5 billion inner-planet orbits.)



But what specifically drives those instabilities?

Understanding this will help us understand the properties of the real (Gyr+ old) observed multi planet systems!

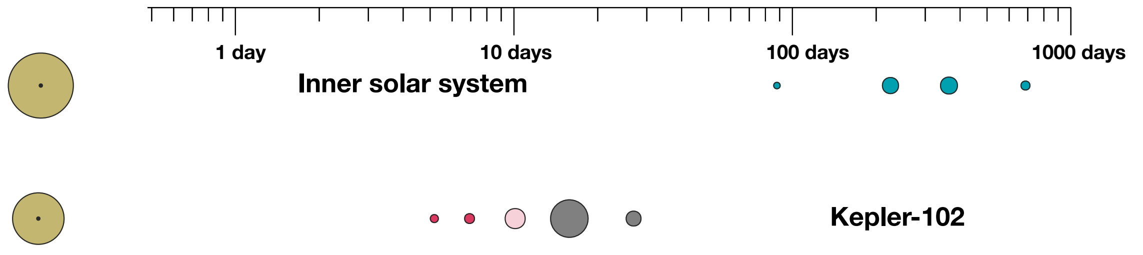


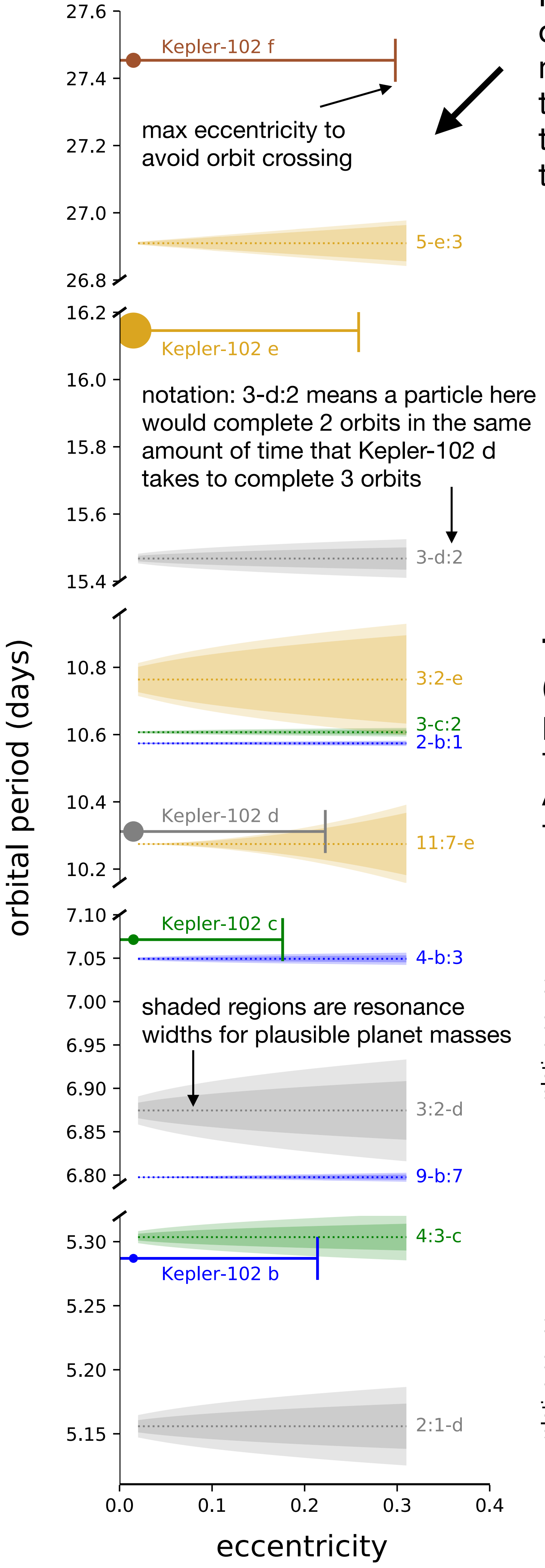
direct instability tends to happen only at small spacings

But unstable planet pairs span the full range of spacings!

We use the 5-planet Kepler-102 system as a case study to understand what's driving instabilities:

This system has a few features of interest:
—very few simulated versions are stable
—the two smallest, inner-most planets are almost always the ones that become unstable
—there are several near-resonant period ratios in the system



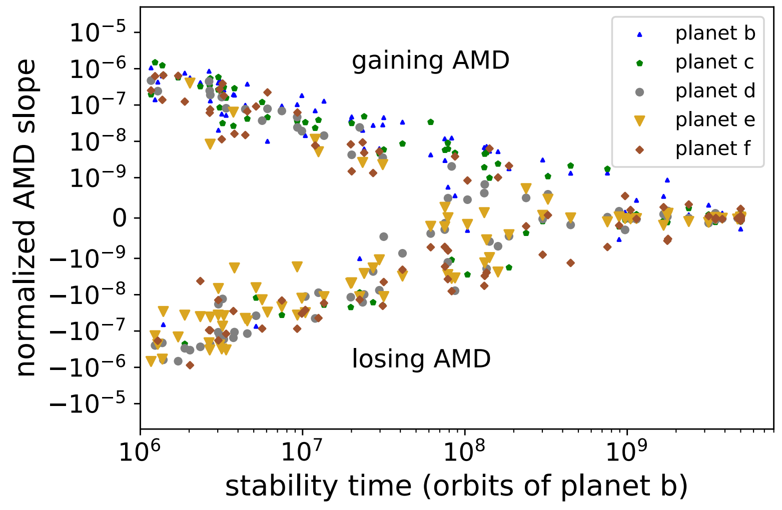


max eccentricity to avoid orbit crossing

notation: 3-d:2 means a particle here would complete 2 orbits in the same amount of time that Kepler-102 d takes to complete 3 orbits

shaded regions are resonance widths for plausible planet masses

However, at the low eccentricities typical of Kepler multis and for reasonable planet masses (based on planetary radii), none of the planets are actually close enough to their mutual mean motion resonances for those to directly drive the instabilities.



Instead, **the instabilities appear to be the result of angular momentum deficit (AMD) being transferred inward** (the plot illustrates the change in AMD per orbit for each planet in all our Kepler-102 simulations).

$$AMD_{total} = \sum_{j=1}^{N} AMD_j$$

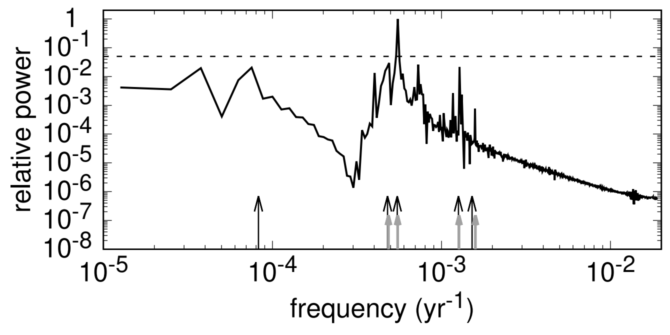
$$AMD_j = \frac{m_j M_*}{m_j + M_*}\sqrt{G(m_j + M_*)a_j}\left(1 - \sqrt{1-e_j^2}\cos i_j\right)$$

Because the inner planets are small, even a slight increase in AMD can raise their eccentricities to unstable values.

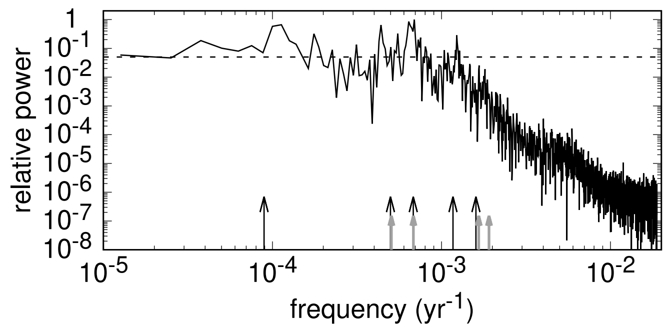
If Kepler-102 b's mass is >~0.1M⊕, stability is more likely.

The inward transfer of AMD in this system and many others is driven by secular chaos (e.g., Lithwick & Wu 2011). We calculated "spectral fractions" to describe the AMD of each planet in a simulated system based on very short (~10^6 orbit) integrations; the spectral fraction is the fraction of frequencies in a discrete fast Fourier transform (FFT) of a planet's AMD time series that exceed some power threshold (we chose 5% of the strongest frequency).

Low spectral fraction:



High spectral fraction:



The spectral fraction calculated from short simulations (~10^6 orbits) is a good predictor of stability on long timescales (~10^9 orbits)! Below we show the distribution of survival times (median and 1-sigma spread) vs spectral fraction for a few thousand simulations of Kepler multis.